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EXPERIMENTAL INVESTIGATION OF THE ABLATION OF BODIES

BY HYPERSONIC FLOW

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Translation of: Eksperimental'noy issledovaniye oplavleniya tel sverkhzvukovym potokom

[redacted]

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EXPERIMENTAL INVESTIGATION OF THE ABLATION

OF BODIES BY HYPERSONIC FLOW

-USSR-

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The fall of meteorites in the lower layer of the atmosphere results in a fast disintegration due to ablation and vaporization. In this connection, it is interesting to obtain experimental data characterizing the process of disintegration of meteorites. The first studies in this direction were made by Tomas and Whipple, [1], Allen et al., [2], and Maclean [3].

The present work analyzes experimentally the process of body ablation by a hot supersonic flow of high density. The mechanism of the ablation of the body by such supersonic flow closely resembles the mechanism of the atmospheric effect to which the meteorite is subjected while flying through the lower layers of the atmosphere down to the impact area.

The following methods of investigation were accepted: The model to be investigated was rapidly introduced into hypersonic flow with the temperature of flow stagnation exceeding the temperature of body melting. The process of ablation was observed visually and was photographed with a motion picture camera. Attention was paid to the shape and form of the models after ablation.

As a result, general laws of the process of body ablation were obtained, as well as quantitative data on heat transfer in the wide range of the parameters of experiment. The effect of the mechanical disintegration of material was not taken into account.

A. Experimental Ways and Means

In order to obtain a hot hypersonic flow, gasodynamic installations equipped with heaters were used. Efforts to expand the range of parameters under which the experiment was performed lead to the use of three such installations.

Installation No. 1 was provided with a flow of M = 1.7. The discharge cross-section of the nozzle was 27 X 27 mm. The temperature of flow stagnation: 80-100°. The installation operated between pressure and a vacuum.

Installation No. 2 had the following parameters: $M = 1.7$, flow pressure — atmospheric; stagnation temperature: 100—1,000°.

The third installation was characterized by the following data: $M = 2.84$, pressure in the flow 0.66 at, temperature of the adiabatic stagnation 2,800° K.

For models we used the rotational bodies in the shape of cylinders of various cross-sections (6—160 mm) and cones with angles of 10—60°. They were made of metal differing greatly one from another in their physical properties: Wood's alloy, tin, lead bismuth, zinc, aluminum, steel.

The models under investigation were placed along the axis of the nozzle at some distance from its tail end. The ablations process was observed through Tepler's shadograph and was photographed with the KS-50B motion picture camera.

Results were obtained in form of diagrams showing the decrease in length of the model part ablated with time, photographs of the successive stages of the ablation process, and the forms of models after ablation.

B. Results of the Experiments. General Picture of Ablation.

Fig. 1 shows the photographs of the three different stages of ablation of a cone-type model made of aluminum. [See Figure Appendix] The experiment was conducted on the 2nd installation at a stagnation temperature of 850°. Ablation of other models proceeded in the similar way. The enclosed photographs show that the most intensive melting occurred on the frontal blunted part of the model, behind the shock-wave. It must be noted that the frontal part of the model, even if it had been previously tapered, always becomes blunted. The ablation process is accompanied by the blow-off of the melted metal from the melting surface; later, this metal flows down the lateral surface as a film, more or less thick.

Fig. 2 shows the initial contours of the models made of lead and tested at installation No. 2 at a temperature of 310°. [See Figure Appendix] Marked also in the position taken by ablation surface at various time moments. These positions of the ablation surface were obtained by the method of processing the photographs, similar to those shown in Fig. 1. It can be seen from the diagram that the ablation front very soon acquires a stable form, independent of time and initial configuration of the model.

Analysis of diagrams, representing the results of experiments with models made of different material and under different conditions of experimentation, confirms the above proposition.

Comparison of diagrams has showed that, in case of small Reynolds numbers ($R \approx 10^4 \div 5 \cdot 10^4$), the shape of the ablation surface approaches the ellipsoid with the ratio of semi-axes near 0.5. When the Reynolds number is increased, the shape of the ablation surface becomes more acicular and in the range of $Re = 1 \cdot 10^5 \div 5 \cdot 10^5$, it acquires the form of a spherical frustum of a cone. This cone can be clearly seen in Fig. 3 which shows a photograph of a cylinder after its ablation which originally had a flat end plane. In experiments conducted at $M = 1.7$, the angle at the apex of such cone was 60—80°; however, variation within these limits occurred not only in different experiments, but even during the ablation of the same model. As if the ablation surface would oscillate around its stable state, while the angle at the apex of the cone's melting surface became alternately greater or smaller.

Fig. 4 shows a photograph of the oriented Karakol meteorite. As can be seen from this photograph, ablation of the oriented meteorite leads to the formation of the specific shape of the melting part which has the form of a spherical frustum of a cone. The oriented Zabrod'ye meteorite is of a similar shape. For some such meteorites, the angle at the apex of the cone varies within the limits of 75—95°, which comes very close to the corresponding values obtained in our experiments.

An exception to this rule were cylinders with a flat front end, made of bismuth and zinc. During ablation of these models, the melting surface remained flat and perpendicular to the flow axis throughout the process. In this case, as is seen in Fig. 5, the melting of the end plane of the cylinder is accompanied by an intensive ablation of the lateral surface. The maximum of that ablation is located at the distance of one caliber from the frontal melting end; this is attributed to the specific airflow around the cylinder with the flat frontal end /4/.

Experiments with cylinders made of bismuth and zinc were conducted under the same conditions of airflow and heat transfer, as the above described experiments.

If we limit ourselves to the analysis of external and internal functions of heat transfer, then it becomes difficult to explain the variable character of ablation of originally identical models made of various materials. Evidently, a more detailed description of the process requires an analysis of some other values characterizing the physical and mechanical interaction between the hypersonic flow and the body under melting conditions.

One of the most typical signs of a meteorite are the characteristic dents on the melting surface, known as "regmaglipts"./5/ The nature of the regmaglipts and the dependence of their form and size on external factors is not yet clear at present. In the experiments, described here, it was possible to obtain for the first time the analogous structure under laboratory conditions. (Fig. 6).

It was found that, under the identical airflow conditions, the regmaglipts were not always formed, but only in ablation of certain materials. In our experiments, such materials were: bismuth, zinc, lead, and steel. It was also established that the size of remaglipts was proportional to the size of the model. It is interesting to note that a similar relationship was also found in meteoritics. Observation of regmaglipts' surface during various moments of body ablation makes it possible to conclude that the size of regmaglipts does not change in the process of body ablation by the flow, but, other conditions being equal, depends only on the characteristic size of the body.

Should further experiments make it possible to establish precisely the relationship between the characteristic sizes of regmaglipts and the body on which they were formed, then a new method to estimate the original size of a meteorite may be found.

C. Heat Exchange on the Frontal Surface

It was shown above that every body, even if previously tapered, becomes blunted during the ablation by hypersonic flow. Further melting proceeds most intensively only on the frontal blunted surface.

In processing the motion pictures of ablation, it was possible to obtain the diagram of the shift of frontal ablation surface with the time. Fig. 7 shows such a diagram of the decrease in length of the ablated part of the model; it was obtained as a result of experiments with cones made of lead and having different angles at the apex of the cone. It can be seen from the diagram that the speed of ablation of cones remained constant during the entire process of experimentation. [See Figure Appendix]

Knowing the velocities of ablation, we may try to evaluate the heat transfer on the melting surface. The magnitude of heat flow per unit of surface can be found from an analysis of the equation of heat balance on the melting surface. Let us assume that the front of melting is shifting equidistantly; that the metal, blown off from the ablation surface is not forming a superheated film; that, under the conditions of experiment, the radiation from the melting surface is negligible. We also assume that the heat transfer from the surface to the interior of the body, due to heat conductivity, is only negligible. Then the equation of heat balance on the melting surface becomes very simple:

$$q = K \gamma r \zeta ,$$

where q is heat flow per unit of the melting surface; γ and r are specific weight and the hidden heat of the melting of model's material; ζ is the velocity of ablation front shifting along the axis of the model; $k \leq 1$ is the coefficient which takes into account the fact that the hidden heat of the melting surface is not fully realized because of the mechanical carry-off of non-melted particles of material from the ablation surface.

Experiments in ablation of the bodies by a low-velocity flow [6,7], demonstrate that the value of k is in this case close to a unit (1). Its determination in our experiments is very difficult. Therefore, in first approximation and in analogy with [6] and [7], the value k was accepted as equal to 1. Then the computation formula for determining the heat transfer coefficient d is as follows:

$$d = \frac{\Upsilon \; r \; \zeta}{To - T_{mlt}}, \qquad (1)$$

where To is the temperature of adiabatic stagnation of the flow; T_{mlt} is the surface temperature equal to the temperature of the melting of material. Only the results of those experiments, where the heat transfer from the melting surface to the interior of the body did not exceed 10--15% of that part of heat which is used for the change of aggregate state at the ablation surface, were processed according to the formula (1). Exception was made only for experiments with cylinders on Installation No. 3; in these experiments, as was shown by calculations, it was necessary to take into account that part of the heat which goes for the heating-up of the material from the initial temperature to the melting temperature.

Data on the heat-transfer coefficients were processed in the form of a dimensionless relationship:

$$Nu = AVn \, Re^{\beta} \, Pr^{0.4}, \qquad (2)$$

where Nu, Re, Pr are Nusselt, Reynolds, and Prandtle numbers respectively; n is proportionality factor in the relationship between the dimensionless velocity and dimensionless coordinate on the blunted surface.

The values of ductility and heat conductivity, included in the expressions for Nu and Re, were referred to the temperature of the wall (of melting), while the velocity was taken as equal to the critical velocity. The dimensionless velocity and the coordinate were obtained by relating the corresponding values to the critical velocity and characteristic dimension. The values n were found on the basis of data in [4]. In the formula (2), the value n was substituted for the zone close to the critical point.

This form of relationship was selected because the theoretical formula for heat transfer on the frontal blunted surface can be reduced to an analogical form.

Results of the experiment, formulated as the dependence of Nu on $Re/aPR^{0.4}$, are represented on Fig. 8. [See Figure Appendix]

The location of the obtained experimental points made it possible to describe the heat transfer on the blunted surface by the formula:

$$Nu = 0.0117\sqrt{n}\, Re^{1} Pr^{0.4} \quad .$$

This formula encompasses a wide range of Reynolds numbers and materials used in the experiment and may therefore be regarded as experimentally corroborated within the following limits:

$Re = 8 \cdot 10^{3} \div 7 \cdot 10^{6}$; $M = 1.7 \div 2.84$ for melting of models made of Wood's alloy, tin, lead, zinc, aluminum, and steel in the range of flow stagnation pressure of 0.8—5.9 at and with changes of the characteristic dimensions of models within the limits of 0.5 to 160 mm.

It must be noted that the character of the obtained dependence of the heat-transfer coefficient upon the Reynolds number is somewhat conditional, since all visible decrease in the linear dimension was attributed to melting. In this connection, the heat-transfer coefficient should have taken into account the mechanical desintegration which was not considered in the present work.

Comparison of data, obtained on the heat transfer in melting on the frontal blunted part, with the theoretical and experimental data on heat transfer on the blunted surface without melting, makes it possible to grasp the essential difference which consists in the following: for the heat transfer with melting, the exponent at Re is close to a unit (1), while from the theory of Reynolds numbers, appearing in the experiment, the exponent should be equal to 0.5., which corresponds to the heat transfer on the laminar boundary layer. The absolute value of the heat-transfer coefficient also exceeds considerably (several times) the data obtained on the basis of the theory.

The causes for such a divergence are not yet clearly understood; they may be explained by the failure to take into account the mechanical disintegration of the model, as well as by turbulent effect of the liquid film flowing down the ablation surface.

D. Conclusions

The present work elucidates experimentally some problems of interaction between the hypersonic flow and an axially-symetric body during its ablation.

The experiments were performed within wide limits of changes in flow parameters: $M = 1.7 \div 2.8$; $T_0 = 400 \div 2{,}800^{\circ}K$, $Re = 8 \cdot 10^{3} \div 7 \cdot 10^{6}$, with models made of various materials (Wood's alloy, tin, lead, bismuth, zinc, aluminum, steel). Cone and cylinder were selected as shape of models.

It was established that in all cases (1) the melting is most intensive on the frontal blunted part of the body, behind the shock-wave. In a cone which had been previously tapered the melting started at the peak point, blunting it. (2)

It has been shown that the shape of the blunted surface of melting depends upon the parameters which characterize the airflow and the heat transfer. In the experiments with Wood's alloys, tin, aluminum, and steel, this shape, in case of small Re, approaches the blunted ellipsis with the ratio of semi-axes equal to 0.5. As the Re increases, the shape becomes more pointed, and with $R > 1 \cdot 10^5$ it acquires the form of spherical frustum of a cone with the angle at the apex of the cone approaching the angle of the frontal surface of an oriented meteorite.

(3) The frontal melting surface of cylinders made of zinc and vismuth remained, under same conditions of experiment, flat and perpendicular to the direction of flow during the entire experiment. This difference can hardly be explained solely by a complex of values describing the heat transfer on the surface and the distribution of temperature in the body.

A regmaliptic structure of the ablation surface, which is characteristic for meteorites, was for the first time obtained under laboratory conditions. Obtained was also a dimensionless experimental formula for the heat transfer on the frontal melting surface of the body subjected to hypersonic flow.

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FIGURE APPENDIX

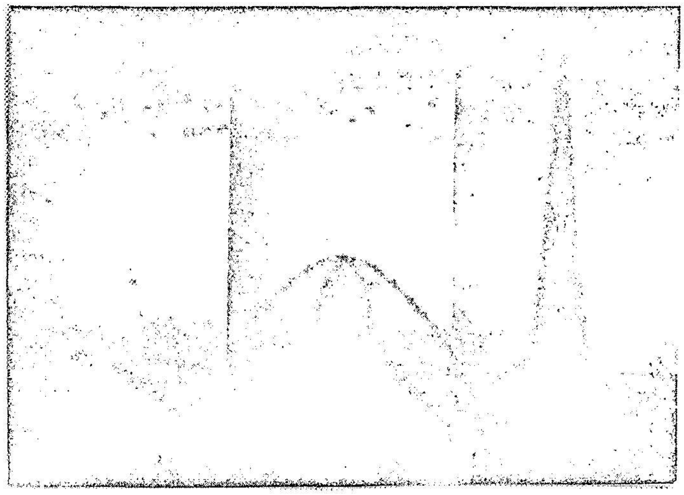


Figure 1

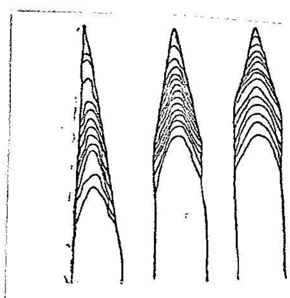


Figure 2

Figure 3

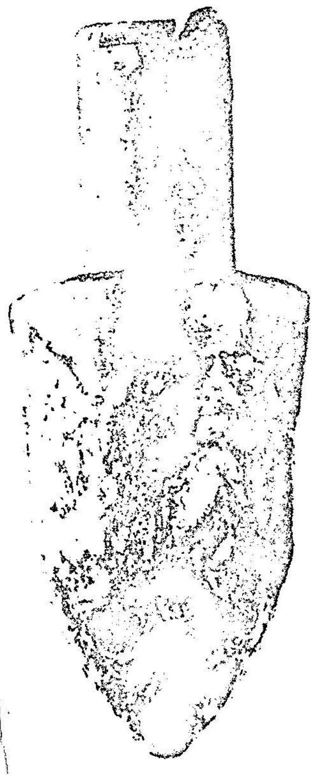
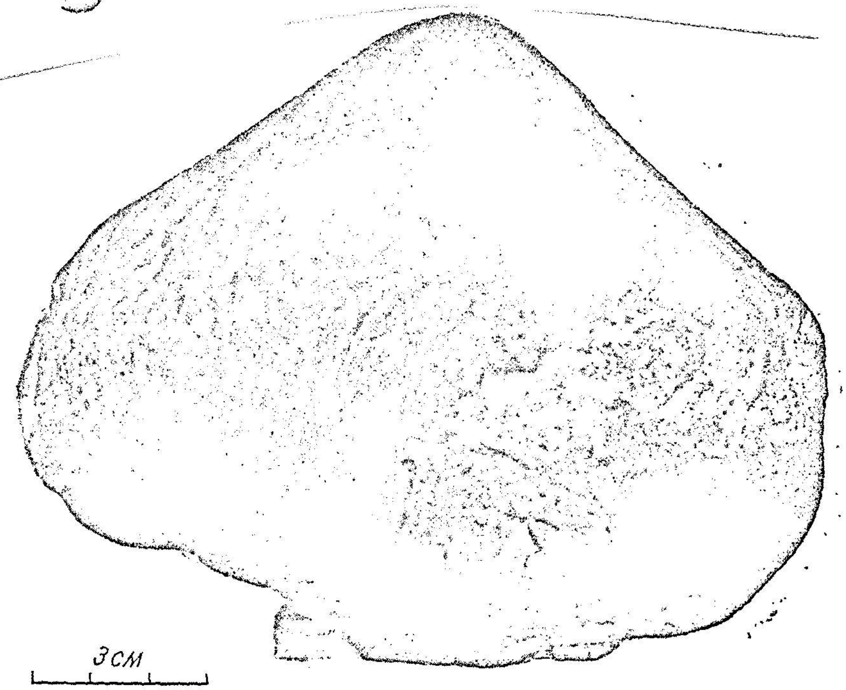


Figure 4



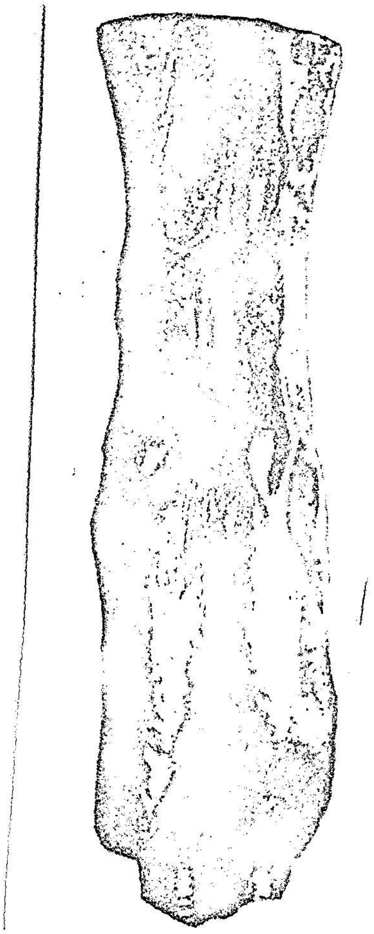


Figure 5

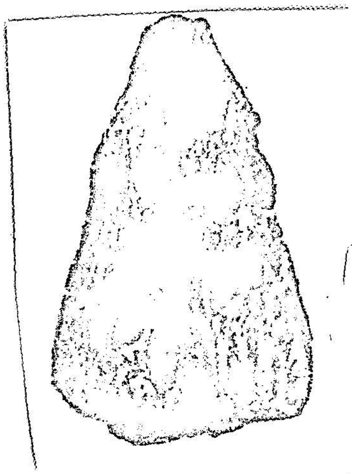
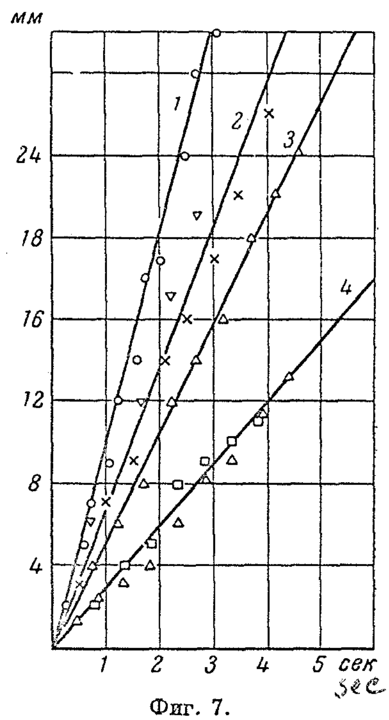


Figure 6



Фиг. 7.

1 — $\theta = 10°$; 2 — $\theta = 20°$; 3 — $\theta = 30°$; 4 — $\theta = 60°$

Figure 7

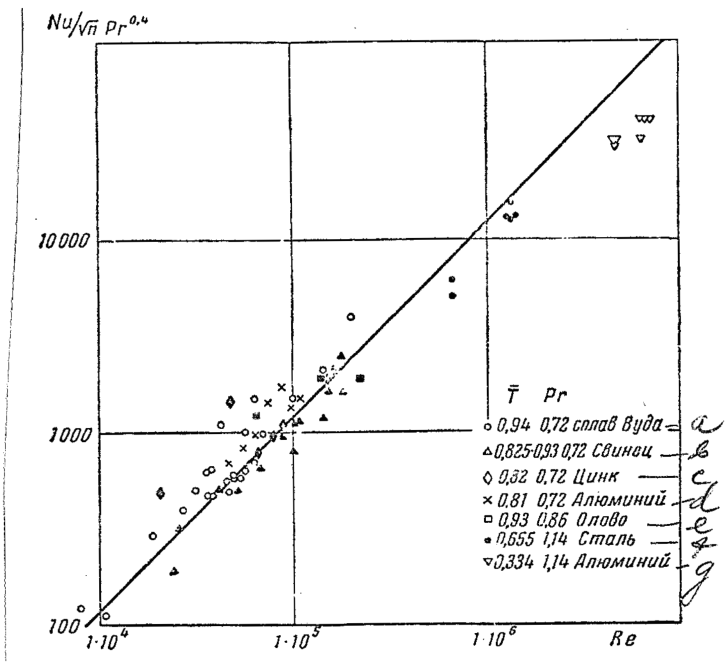


Figure 8. Legend: a - Wood's alloy
b - lead
c - zinc
d - aluminum
e - tin
f - steel
g - aluminum

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